

Research Article

Booms and Busts in Chinese Agricultural Markets: An Agent-Based Model

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This paper uses agent-based modelling to study the frequent booms and busts in Chinese agricultural markets. First, an artificial agricultural commodity market consisting of heterogeneous agents, such as producers, consumers, and speculators, is built. A numerical simulation suggests that speculation can cause large price fluctuations via nonlinear price dynamics. Then, parameters are estimated by the simulated method of moments using garlic and ginger price data in China from 2006Q2 to 2018Q3. The estimation yields a statistically significant speculative behavior parameter, supporting speculators' existence. Based on the well-estimated model, a low-cost policy experiment aiming at market stabilization is carried out. The essence of this policy is to release the theoretical steady state of the estimated model as the government-guided price to producers. The guided price, even partially followed by producers, can reduce simulated price variances and weaken speculators' negative impact on market stability. Robustness tests show that the effect of policy experiment is robust under a 20% change in any parameter value or a 5% change in the guided price.

1. Introduction

Booms and busts are frequently seen in Chinese agricultural markets. Though economists devote most of their attention to financial bubbles and crises in their research, large price fluctuations in financial markets fail to cause a direct impact on most Chinese households because of the low financial market participation rate in China [1]. By contrast, significant price changes in agricultural commodities usually hit almost all households in a direct and perceivable way, as agricultural products appear on the dining tables of every household daily. Therefore, booms and busts in Chinese agricultural markets are worth studying.

The reasons behind the large and persistent price changes of agricultural products are varied and multiform, including factors such as the weather [2], natural calamities, and livestock diseases. (Pork is a typical example of price booms and busts in China. The latest pork boom and bust happened from the beginning of 2019 to the end of 2021. The pork prices rose from 12 CNY/kg in January 2019 to 34 CNY/kg by the end of 2019, almost tripling within a year. The pork prices stayed at a

high level throughout 2020, and then dropped from 36 CNY/kg in January 2021 to less than 11 CNY/kg by October 2021. It is widely acknowledged that the 2019–2020 pork bubble was directly caused by the African swine fever that swept across China in 2018 and 2019, leading to a considerable imbalance between market supply and demand. On January 8th, 2021, Dalian Commodity Exchange started trading live hogs, indicating the first future regarding the pork trade.) [3] Besides these natural causes, artificial factors such as market friction, inefficient supply chain, speculation, and others may also play a role in price changes. Figure 1 shows the detailed price trends of garlic and ginger in Chinese domestic markets from 2006 to 2018. Both prices had increased by more than five times from the lowest to the highest. The most considerable quarterly price changes were 83.68% in garlic and 69.46% in ginger. Chinese and international media reported them as the “garlic bubble” and “ginger bubble.” Scholars argue that speculation is responsible for such agricultural price swings in China [4, 5]. In the present paper, we incorporate this factor into a theoretical model and explore a possible price stabilizing policy.

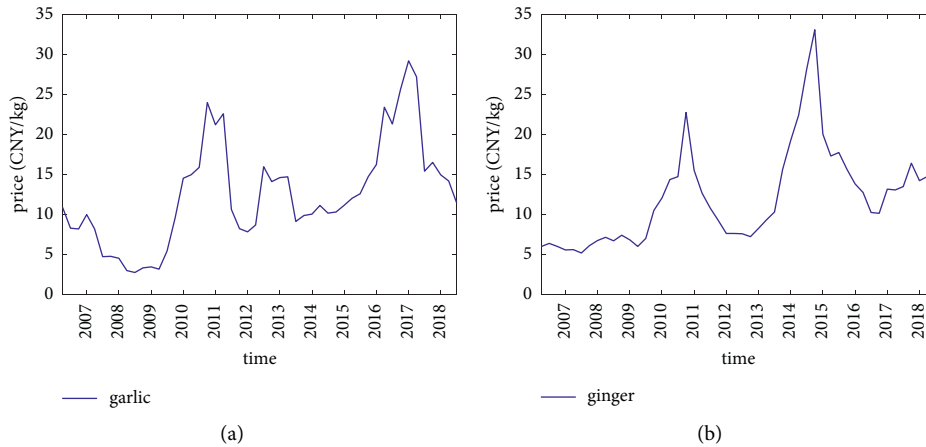


FIGURE 1: Quarterly price of garlic (a) and ginger (b) in China from 2006Q2 to 2018Q3.

Among so many kinds of agricultural commodities, one may ask why we chose to study garlic and ginger. Zhang et al. [6] point out that garlic and ginger have geographically concentrated origins, small market size, ease of storage, and less government intervention, making garlic and ginger easily manipulated by speculators. Moreover, until now, no agricultural future has taken garlic or ginger as the underlying commodity in domestic and international futures markets. Therefore, garlic and ginger markets can be treated as closed domestic markets in which the demand-supply relation and speculation play major roles in booms and busts. Furthermore, factors like the interaction between futures and spot prices and the risk transmission between Chinese and international futures markets do not exist. (As a comparison, agricultural products with well-developed futures include soybeans, corn, and wheat. The existence of well-developed futures markets can be a double-edged sword. On the one hand, corresponding futures can hedge against large price fluctuations in the future, therefore stabilizing spot prices. On the other hand, fluctuations of future prices in the international market may propagate to the domestic market, destabilizing domestic spot prices. When analyzing booms and busts in these markets, the interaction between spot and future prices and the interaction between domestic and international futures markets cannot be ignored. A new model that covers these interactions needs to be developed.)

Researchers call price bubbles fueled by speculative activity “speculative bubbles.” Previous literature on speculative bubbles in agricultural commodity markets mainly concentrates on detecting speculative bubbles by using methods such as the supremum Augmented Dickey–Fuller test [7], duration dependence test [8], and momentum threshold autoregressive approach [9]. Gilbert [7] finds speculative bubbles in soybeans from 2006 to 2008, but not in corn and wheat. Li et al. [4] find speculative bubbles in most Chinese agricultural commodity futures markets from 2006 to 2014. Based on these empirical works, we embed speculators into our model without questioning their existence.

Since drastic price fluctuations of agricultural products negatively influence households’ daily living and market expectations, arousing extensive social concern in China,

agricultural commodity price stabilization has attracted the attention of policymakers and researchers. Studies on price stabilizing policies in agricultural markets primarily focus on their microeconomic benefits [10, 11]. The price stability of agricultural commodities is critical to the stability of producer incomes and consumer expenditures [10]. Massell [11] shows that price stabilization increases social welfare through a positive change in the sum of producer and consumer surplus. Despite the theoretical desirability of improved stability, stabilization policies commonly used in practice, e.g., price limiters such as price ceilings or floors, have a few disadvantages. For instance, an inappropriately high price floor may result in overproduction [12]. Price limiters can also generate substantial fiscal costs due to maintaining a buffer stock [13]. Therefore, it is essential to explore new options.

Studies most relevant to our work incorporate speculators as a destabilizing force in agent-based models (ABMs) of commodity markets. He and Westerhoff [14] built a log-linear commodity market model composed of producers, consumers, and speculators. They investigated the influence of conditional price limiters jumping between bottoming and topping limits on model price dynamics, finding that the conditional price limiters efficiently reduce these fluctuations. Westerhoff and Wieland [15] developed a behavioral cobweb model with linear supply and demand and speculators who can switch between fundamental and technical trading rules. Variations in the number of speculators cause price bifurcations. Though speculators are destabilizing the market on average, they can stabilize prices in certain situations, and thus banning them from trading commodities is not necessarily wise. Fernandez-Mena et al. [16] built an ABM to study the flows in agro-food networks. They simulated material exchanges for a small region in France and found that the number of flows is sensitive to distance and shared interest between agents.

This paper develops and estimates an ABM of agricultural commodities to study the impact of speculation on price stability. Three kinds of heterogeneous agents participate in the market: producers, consumers, and speculators. On the supply side, producers have linear backward-looking expectations and an S-shaped production function. Consumers with rational

expectations and speculators with extrapolative expectations coexist on the demand side. A theoretical model analysis suggests speculation may indirectly cause endogenous price fluctuations by influencing producers' expectations. Using the simulated method of moments (SMM) estimation and quarterly garlic and ginger prices in China from 2006Q2 to 2018Q3, our model suitably captures empirical price features. The significance of speculators' trend extrapolating parameter implies that their speculative demand nourishes the garlic and ginger bubbles. Then, based on the well-estimated model, a low-cost price stabilizing policy experiment is conducted. The proposed policy reveals the estimated model's theoretical steady states as the government-guided prices to producers. When a portion of producers uses the guided prices to replace their original expectations, they adjust their production and supply accordingly. Via market clearance, the speculators' impact on market prices is weakened, the simulated price variance drops, and the market stability improves.

The rest of this paper is organized as follows: Sections 2 builds an agent-based model and discuss its nonlinear price dynamics. Section 3 estimates the model by the simulated method of moments. In Section 4, a price stabilizing policy experiment is conducted. The robustness of policy experiment is tested in Section 5. Finally, conclusions and policy implications are proposed in Section 6.

2. Agent-Based Modelling

The method of ABMs first appeared in the 1970s and started flourishing in the 1990s when the computing power of computers sharply increased. The most significant feature of such models is the existence of multiple heterogeneous agents representing economic subjects, whose behavior is designed to mimic human subjects. When ABMs are used to study macroeconomic problems or financial markets, the bottom-up structure of ABMs naturally bridges microeconomics and macroeconomics. After more than 30 years of rapid development, there are several handbooks and collections of works reviewing ABMs comprehensively. Please refer to Tesfatsion and Judd [17] and Hommes and LeBaron [18] for more information.

This section designs a simple ABM for an agricultural commodity and derives a degenerate case of the model without the presence of speculators. Figure 1 shows that the garlic and ginger bubbles grew and burst over the years, implying that these bubbles are beyond the explanation of seasonal factors and production cycles. Natural cyclical factors in the production of agricultural products are neglected, and artificial factors, such as decision-making by market participants and trading among participants, are emphasized to ensure that the proposed model focuses on the impact of speculation on market prices. Section 2 ends with a comparison between the numerical results of the original ABM and the degenerate case.

2.1. Heterogeneous Agents and Market Clearance. In the proposed ABM, the artificial market is filled with three kinds of heterogeneous agents: producers, consumers, and speculators, shown by a superscript P , C , and S , respectively. At

each period t , heterogeneous agents first update their expectations. Producers, consumers, and speculators' expectations are denoted as $P_{e,t}^P$, $P_{e,t}^C$, and $P_{e,t}^S$. Agents' expectations are updated according to the following rules:

$$P_{e,t}^P = wP_{t-1} + (1-w)P_{t-2}, 0 < w < 1, \quad (1)$$

$$P_{e,t}^C = P_t, \quad (2)$$

$$P_{e,t}^S = P_{t-1} + \gamma(P_{t-1} - P_{t-2}), \gamma > 0. \quad (3)$$

Producers have linear backward-looking expectations [19]. $P_{e,t}^P$ is the weighted average of the past two periods prices. Parameter w measures the weight of P_{t-1} in the producers' expectations. Consumers have rational expectations (The rationale behind this assumption is that consumption decisions tend to be made more quickly and easily compared to the time and effort the production process takes. We provide an example, the reference prices usually seen in some farmers' markets in China, and some discussion in the last section.), and $P_{e,t}^C$ is not adaptively formed using past information. Speculators form $P_{e,t}^S$ by extrapolating past price trends. The larger γ is, the more intense the extrapolation is. After the expectations are updated, agents then decide the amount to supply or purchase. An S-shaped supply schedule is adopted, which is appropriate if fixed costs are high at low output levels and capacity constraints come into force at high output levels [20]. The producers' supply is expressed as follows:

$$S_t = \arctan\left(c(P_{e,t}^P - d)\right) + e. \quad (4)$$

The consumption demand D_t^C is linear in the consumers' expected price of period t , while speculative demand D_t^S is linear in speculator's expected price of period $t+1$.

$$D_t^C = a - bP_{e,t}^C, \quad (5)$$

$$D_t^S = a - bP_{e,t+1}^S. \quad (6)$$

The market clears when the total supply S_t intersects with the total demand D_t . The total demand is the weighted sum of the consumption demand and speculative demand.

$$S_t = D_t, \quad (7)$$

$$D_t = N_t D_t^C + (1 - N_t) D_t^S. \quad (8)$$

Here, N_t is the fraction of consumers, and $1 - N_t$ is the fraction of speculators. The switching of buyers between the consumption motive and speculative motive follows the Brock and Hommes [21]. N_t can be expressed as the following multinomial logistic model:

$$N_t = \frac{e^{\varepsilon \pi_{t-1}^C}}{e^{\varepsilon \pi_{t-1}^C} + e^{\varepsilon \pi_{t-1}^S}}. \quad (9)$$

If $\varepsilon > 0$, the share of speculators is a monotonic increasing function of π_t^S , which is the performance measure of speculators. Speculators consider the commodity as a financial asset, so their performance measure equals the

capital gain in (10), where R is the gross risk-free rate. Consumers' performance measures are set to 0.

$$\pi_t^S = (P_t - RP_{t-1})D_{t-1}^S, \quad (10)$$

$$\pi_t^C = 0. \quad (11)$$

Equations (1)–(11) constitute the ABM for the agricultural commodity. The steady-state price P^* for the model satisfies that

$$\arctan(c(P^* - d)) + bP^* = a - e. \quad (12)$$

2.2. Degenerate Case without Speculators. A degenerate case of the ABM is now considered, where $\gamma > 0$ is violated and γ becomes zero. Speculators' expectations, represented by (3), becomes

$$P_{e,t}^S = P_{t-1}. \quad (13)$$

Demand originated from speculators, represented by (6), becomes

$$D_t^S = a - bP_{e,t+1}^S = a - bP_t. \quad (14)$$

Because (14) and the consumption demand in (5) are identical, one may conclude there is no speculation when $\gamma = 0$. The degenerate case is written as follows:

$$\begin{cases} P_{e,t}^C = P_t, \\ P_{e,t}^P = wP_{t-1} + (1-w)P_{t-2}, 0 < w < 1, \\ S_t = \arctan(c(P_{e,t}^P - d)) + e, \\ D_t^C = a - bP_{e,t}^C, \\ S_t = D_t^C. \end{cases} \quad (15)$$

2.3. Price Dynamics with and without Speculators. To unveil the channel through which speculation may induce price fluctuations, the original ABM and the degenerate case are investigated numerically, and their results are compared.

Figure 2 presents the bifurcation diagrams of w drawn using the following parameter set: $a = 8$, $b = 0.44$, $c = 2$, $d = 9.6$, $e = 1.5$, $\gamma = 0.089$, $\varepsilon = 0$, and $R = 1.0186$. The values of γ , ε , and R only apply to the original ABM. The results of the original ABM are shown in Figure 2(a), while the results of the degenerate case are provided in Figure 2(b).

3. Estimation

This section estimates (Please see Hansen and Heckman [23] and Kydland and Prescott [24] for model estimation and calibration. Chen et al. [25] compare several methods widely used in model estimation.) the model via simulated method of moments (SMM) by using the ABM as an artificial laboratory to scrutinize the effects of potential stabilization policies on China's agricultural commodity price.

Subsection 3.1 briefly introduces the estimation methodology and the data used. Subsection 3.2 presents the estimation results.

3.1. Simulated Method of Moments. Using the SMM approach [26, 27], where the core idea is to match model-generated moments with empirical moments, the parameter vector $\theta \equiv \{a, b, c, d, e, w, \gamma, \varepsilon, \sigma\}$ is estimated, where σ is the standard deviation of the noise term used in simulations. Here, $R = 1.0186$ to yield a reasonable gross risk-free rate. This paper uses a sample composed of quarterly price data (Data source: <http://www.chinabric.com>) of the two commodities from 2006Q2 to 2018Q3 to justify the argument that speculation is responsible for garlic and ginger price instability in China. Each time series has $N = 50$ observations, let \hat{m} be the moment vector of model-generated log returns, computed based on $K = 200$ simulations of N observations. Let m be its empirical counterpart. Formally, the SMM estimator of θ is expressed as

$$\hat{\theta}_{SMM} = \arg \min J(\theta), \quad (16)$$

$$J(\theta) = \frac{NK}{1+K} (\hat{m}(\theta) - m)^T W (\hat{m}(\theta) - m), \quad (17)$$

where W is a positive definite weighting matrix. To ensure the efficiency of the estimation results, the optimal W is the inverse of the variance-covariance matrix of $(\hat{m}(\theta_{true}) - m)$ [28]. θ_{true} is a vector of true values of unknown parameters.

The optimal weighting matrix is approximated via a two-step variance-covariance estimator. First, we use an identity matrix as the weighting matrix (i.e., $W = I$) and minimize the objective function to get a preliminary SMM parameter vector $\hat{\theta}_1$.

$$\hat{\theta}_1 = \arg \min \frac{NK}{1+K} (\hat{m}(\theta) - m)^T I (\hat{m}(\theta) - m). \quad (18)$$

Then, we employ $\hat{\theta}_1$ to conduct simulations and compute the variance-covariance matrix of $(\hat{m}(\hat{\theta}_1) - m)$, denoted as $\hat{\Omega}$. The estimate of the optimal weighting matrix is obtained by further taking the inverse of matrix $\hat{\Omega}$.

$$\hat{\Omega} = \frac{1}{N} (\hat{m}(\hat{\theta}_1) - m)(\hat{m}(\hat{\theta}_1) - m)^T, \quad (19)$$

$$W^* = \hat{\Omega}^{-1}.$$

3.2. Parameter Estimates and Interpretations. By interpreting the estimation results, the impacts of speculation on price dynamics in China's garlic and ginger market are inspected. Table 1 summarizes the estimated parameters of the garlic and ginger markets. Table 2 presents the simulated moments generated after the model estimation and their empirical counterparts.

The results in Table 1 can be interpreted as follows. The J statistic in (17) has an asymptotic chi-square distribution with 1 degree of freedom. The J statistic for garlic is 0.3379, and the J statistic for ginger is 0.2959. The critical value of $\chi^2(1)$ at a 95%

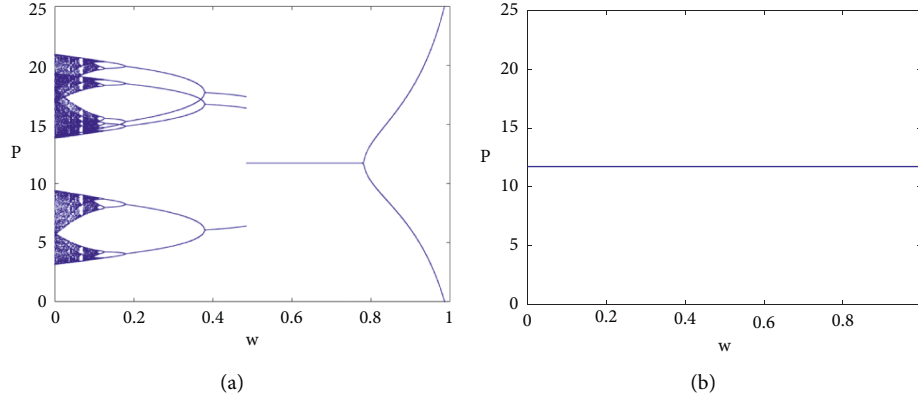


FIGURE 2: Bifurcation diagrams of the parameter w , with all other parameters fixed at $a = 8$, $b = 0.44$, $c = 2$, $d = 9.6$, $e = 1.5$, $\gamma = 0.089$, $\varepsilon = 0$, and $R = 1.0186$. The figures show the existence of single or multiple stable steady states or even chaotic price dynamics under different w -values. The w appears in (1) and (15), denoting the weight of the latest market price in producers' price expectation formation. (a) In the original ABM with speculators, nonlinear price dynamics show various phenomena, such as pitch-fork bifurcation ($w = 0.7703$), period-doubling bifurcation ($0.109 < w < 0.3812$), and chaos ($w < 0.1098$). (b) In the degenerate case without speculators, one single stable steady state of the market price exists under different values of w .

confidence level is 3.84, and the p values corresponding to the two test statistics are 0.5610 and 0.5865. The model is neither rejected by the data of garlic nor by the data of ginger. Despite the small J statistics, to conclude that the real-life price dynamics of garlic and ginger are well captured by the ABM proposed and driven by speculation, the possibility that $\gamma = 0$ also needs to be ruled out. If the estimated γ is not significantly different from 0, the true data generating process may be closer to the non-speculation degenerate case given by (15). The estimated values of γ turn out to be significantly positive and are 0.4182 for garlic and 0.5497 for ginger. Since the parameter γ represents extrapolation strength, a comparison of the parameter values of ginger and garlic shows that ginger speculators have a slightly stronger belief about trend continuation than garlic speculators. The original ABM is favored over the degenerate case by empirical data, denoting that there exists a speculative demand in China's garlic and ginger market. Since speculation indirectly destabilizes prices by influencing producers' expectations in the original ABM, the nonrejection J statistics accompanied by the statistical significance of the estimated γ imply a causal relationship between speculative activities and the excessive price volatility of the two commodities.

Parameter ε is usually called the intensity of choice in ABMs [21], and literature shows that this parameter plays an important role in increasing model complexity [29]. It reveals the herding behavior of buyers between the consumption motive and speculative motive. According to (9), $1 - N_t$ measures how the fraction of speculators at the market demand side evolves with past speculative payoffs: when $\varepsilon = 0$, the fraction of speculators is fixed at a constant level; when $\varepsilon > 0$, a larger positive past speculative payoff attracts more buyers to the speculative motive; when $\varepsilon = +\infty$, buyers are extremely sensitive to positive speculative payoffs, and any positive payoffs can drive all buyers to switch to the speculative motive; and when $\varepsilon < 0$, a negative past speculative payoff makes buyers irrationally switch away from speculative motive. A negative ε does not make any economic sense. With a 1% significance level, ε is estimated as

0.5231 for garlic and 3.3853 for ginger, suggesting the existence of herding behavior among buyers in both markets. Both the share of garlic speculators and ginger speculators increase with positive past speculative payoffs. As a comparison of parameter values, buyers' herding behavior in the ginger market is stronger than buyers' herding behavior in the garlic market.

The supply side and producer behaviors will now be addressed. The estimated values of w are 0.2395 for garlic and 0.3523 for ginger, both significant at the 1% level. According to (1), producers in both markets hold linear backward-looking expectations to some extent. Their expectations for the newest market price are weighted averages of historical prices at the latest two periods. The only difference between producers' expectations is that ginger producers put more weight (0.3523) on the latest price than the garlic producers (0.2395).

Because of space limitations, the present paper does not further interpret other parameters estimated in Table 1. The estimation results indicate that the real-world price dynamics of the two agricultural commodities are adequately captured by the proposed model, and speculation is a possible driving force behind excessive price volatility in China's garlic and ginger markets.

Figure 3(a) shows that the enactment of the policy barely alters the intensity of speculative activities for the two agricultural commodities. In the top panel of Figure 3(a), after policy application, the average share of garlic speculators does not deviate too far away from its prior-policy value of 0.1917 as h , the proportion of producers following government-guided price, varies between 0 and 1. In the bottom panel of Figure 3(a), after policy application, the average share of ginger speculators boundedly fluctuates between 0.3170 and 0.3929 as h varies between 0 and 1, compared with a prior-policy value of 0.3431. Because the government-guidance price policy is merely imposed on producers, this policy does not intervene in speculative activities directly, and the

TABLE 1: SMM estimated parameters for garlic and ginger.

Garlic				Ginger			
a	8.5142*** (0.0098)	w	0.2395*** (0.0075)	a	11.4282*** (0.0913)	w	0.3523*** (0.0277)
b	0.3619* (0.1611)	γ	0.4182* (0.1979)	b	0.0694*** (0.0250)	γ	0.5497*** (0.1541)
c	3.0010*** (0.7862)	ε	0.5231*** (0.0005)	c	1.9924*** (0.0150)	ε	3.3853*** (0.0311)
d	9.6978*** (1.3307)	σ	1.0154*** (0.2932)	d	9.6863 (5.0438)	σ	0.7885* (0.3746)
e	1.3786*** (0.0145)	J	0.3379	e	-1.2438*** (0.0010)	J	0.2959

Note. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$, standard errors in parentheses.

TABLE 2: Sample moments and simulated moments of return series.

Moments	Garlic		Ginger	
	Sample	Simulated	Sample	Simulated
Mean	1.005654	1.012601	0.999997	1.003528
Variance	0.015937	0.019276	0.006618	0.002608
Skewness	1.104322	1.090279	0.391738	0.391610
Kurtosis	4.356395	4.335239	2.465169	2.465194
$\text{Cov}(r_t, r_{t-1})$	0.006836	0.007562	0.003036	0.006368
$\text{Cov}(r_t, r_{t-2})$	0.002303	0.001825	0.001374	0.001931
$\text{Cov}(r_t, r_{t-3})$	0.000946	0.000251	0.000394	0.000493
$E(r_t^2, r_{t-1}^2)$	1.086123	1.047242	1.021625	1.024045
$E(r_t^2, r_{t-2}^2)$	1.067539	1.075341	1.012052	1.013522
$E(r_t^2, r_{t-3}^2)$	1.060742	1.079454	1.007846	1.013871

average market fraction of speculators shows no visible reaction to the policy implementation.

Figure 3(b) shows that the policy leads to an apparent reduction in the simulated average price variances of the two agricultural commodities. Increases in h , either in the garlic or ginger markets, further enlarge the reduction. Generally speaking, the larger the proportion of producers who follow the policy, the smaller the average price volatility becomes. More specifically, in the top panel of Figure 3(b), when h increases from 0 to 1, the garlic price variance almost monotonically decreases from 65.71 to 9.09. In the bottom panel of Figure 3(b), when h increases from 0 to 0.8312, the ginger price variance drastically decreases from 53.47 to 16.06; when h becomes greater than 0.8312, the level of the ginger price variance remains relatively unchanged

Recall that speculation indirectly destabilizes agricultural commodity prices by influencing producers' price expectations. While the policy discussed is unintended and unable to reduce the speculator proportion, it still significantly weakens speculators' negative impact on price stability by protecting producers' price expectations from manipulating speculative activities. When more producers follow the policy, more producers are prevented from adopting the misleading price signals sent by speculators to form producers' price expectations. Therefore, it is unsurprising that an overall negative relationship between h and simulated price variances is presented. In other words, the government-guidance price policy weakens the price expectation formation channel through which speculators can influence market price volatility.

4. A Price Stabilizing Policy Experiment

In this section, a policy experiment is carried out to explore the feasibility of a low-cost price stabilization policy using

the estimation results of garlic and ginger as the empirical microfoundation. Speculation may indirectly cause endogenous price fluctuations by facilitating the destabilizing force of producers' expectations; thus, it might be possible for a central authority to weaken the speculators' impact on the market by guiding producers' expectations.

The intervention strategy reveals a government guidance price to producers. The government-guided price equals the theoretical steady-state price P^* . Because some producers may not necessarily trust the central authority or miss the information released by it, the present paper assumes that a fraction h of producers uses the government-guided price to replace their original linear backward-looking expectations. The price expectation of those who follow the policy is denoted as $P_{e,t}^G$. The new total supply is given by (22).

$$P_{e,t}^G = P^*, \quad (20)$$

$$S_t = h \left(\arctan(c(P_{e,t}^G - d)) + e \right) + (1 - h) \left(\arctan(c(P_{e,t}^P - d)) + e \right). \quad (21)$$

Other setups of the ABM remain unchanged. In the simulations, parameters other than h are assigned the estimated values. The parameter setting of the garlic market is $a = 8.5142$, $b = 0.3619$, $c = 3.0010$, $d = 9.6978$, $e = 1.3786$, $w = 0.2395$, $\gamma = 0.4182$, and $\varepsilon = 0.5231$. The parameter setting of the ginger market is $a = 11.4282$, $b = 0.0694$, $c = 1.9924$, $d = 9.6863$, $e = -1.2438$, $w = 0.2395$, $\gamma = 0.5497$, and $\varepsilon = 3.3853$. Parameter h increases with a minimal increment step of 0.01. Each simulation lasts $T = 5000$ periods. For each parameter combination, the following two statistics are calculated:

The average market fraction of speculators is monitored by calculating the following:

$$\text{weight } S = \frac{1}{T} \sum_{t=1}^T (1 - N_t). \quad (22)$$

The price volatility is measured by the sample variance of the simulated price series.

$$\text{volatility} = \frac{1}{T-1} \sum_{t=1}^T (P_t - \bar{P})^2. \quad (23)$$

The government-guidance price is a low-cost policy because it is suggestive rather than mandatory. The central authority needs to properly calculate and release the guided price to producers rather than force producers to follow the guided price strictly. As this policy is suggestive, it is inevitable that some producers will decide to follow it while

others will not due to different reasons. The parameter h denotes the fraction of producers who follow the government-guided price in their production decision-making process. This parameter is directly related to the breadth of the policy acceptance. Therefore, the analysis of the policy experiment focuses on the parameter h .

Figure 3 illustrates how the average speculator fraction and average price volatility in the garlic and ginger markets react to the introduction of the government-guidance price policy. The dashed lines represent values of the two statistics before policy implementation, and the solid lines represent values of the two statistics after policy implementation.

Recall that variations in parameter w represent the weight of the latest market price in producers' price expectation formation in (1). The larger (smaller) w is, the greater weight producers place on the price of the previous (penultimate) period. In the original ABM with speculation, shown as the panel (a) of Figure 2, changes in the producers' expectations can influence the occurrence and amplitudes of price fluctuations under the parameter set $a=8$, $b=0.44$, $c=2$, $d=9.6$, $e=1.5$, $\gamma=0.089$, $\varepsilon=0$, and $R=1.0186$. More specifically, when $0.4843 < w < 0.7703$, prices generated by the ABM stay in the stable steady state at $P^* = 11.7274$ after the transient periods. If w increases or decreases beyond the interval, the steady state loses its stability, and endogenous price fluctuations arise. At $w=0.7703$, a pitch-fork bifurcation occurs and two stable steady states start to coexist. As w further increases, the two stable steady states diverge. At $w=0.4843$, one stable steady state slips into three stable steady states. As w decreases, period-doubling bifurcations simultaneously occur at all three branches at $w=0.3812$. As w further decreases, more period-doubling bifurcations occur repeatedly. For $w < 0.1098$, the price dynamics exhibit chaotic behavior. In the degenerate case without speculation, shown in the panel (b) of Figure 2, the bifurcation diagrams of w are just one horizontal straight line, implying that producers' expectation changes do not give rise to price volatility changes under the same parameter set.

The features of nonlinear price dynamics determine market price stability. When only one stable steady state exists, the market price can quickly converge to the steady state and remain there. If perturbations or exogenous shocks bring the price away from the steady state, the system can go back to the steady state automatically after the perturbations or exogenous shocks disappear. When multiple stable steady states coexist, starting from any initial price level, to which stable steady state the system will eventually evolved into depends on the attracting basin of each steady state. After the system reaches any stable steady state, any tiny perturbation may trigger the price jump from the old stable steady state to a new one. When the system shows chaotic behavior, the system exhibits what is called sensitive dependence on initial conditions. Any slight discrepancy in two initial price levels can lead to huge differences in later price time series. The price time series do not converge to any price level but may show up at any price level within a bounded domain. Because of space limitations, the present paper will not elaborate further on this issue. For more information on

bifurcations and nonlinear dynamics, please refer to Strogatz [22].

Figure 2 shows the nonlinear price dynamics of the original ABM and the existence of one stable steady state in the degenerate case. The comparison of the price dynamics of those two cases, one with and the other without speculation, lays the theoretical foundation of the posited argument that speculation can endogenously cause large agricultural price fluctuations in price time series since multiple steady states, or even chaotic price behaviors, exist. The comparison in Figure 2 is based on a specific parameter set. Similar comparisons can be conducted under other parameter sets.

5. Robustness Tests

This section examines the robustness of the proposed policy's effects under different model parameters or government-guided price levels. The rationale behind such robustness tests is that, if the central authority adopts alternative estimation methods or their calculation ability is limited, so that their model estimates or guided prices deviate from our calculations, how will the deviations affect the policy's effects. Will the policy experiment still lead to a price variance reduction when parameter estimates or guided prices vary within reasonable ranges?

In the combination of $a, b, c, d, e, w, \gamma, \varepsilon$, and $P_{e,t}^G$, only one parameter or the guided price is tested at a time, and others are all fixed at the values used in Section 4. When a parameter or the guided price is tested, its value deviates from the value used in Section 4 by a given percentage, for example $\pm 5\%$ or $\pm 20\%$. For each alternative combination of $a, b, c, d, e, w, \gamma, \varepsilon$, and $P_{e,t}^G$, this section runs a policy experiment similar to the one in Section 4 with a fixed $h = 0.5$, showing that the guided price is followed by 50% of producers.

Table 3 reports the resulting ratios of $\text{Var}(P_{\text{no intervention}}) - \text{Var}(P_{\text{intervention}})$ to $\text{Var}(P_{\text{no intervention}})$, for which a positive value represents a price variance reduction and a negative value represents a price variance increase after the intervention. Table 3 suggests that the price stabilizing effects of the government-guided policy are reasonably robust. In the original policy experiment conducted in Section 4, the price variance reduction ratio caused by half of producers following the guided price is 15.46% in the garlic market and 50.60% in the ginger market, shown in Figure 3(b) when h is 0.5. As a comparison, if a parameter changes by -5% or $+5\%$ from its estimated value, the price variance reduction ratio varies from 12.28% to 15.02% or from 9.60% to 18.11% in the garlic market and from 50.07% to 51.33% or from 45.71% to 55.11% in the ginger market. The proposed policy's effects is robust under a 5% change of any parameter in both markets. If a parameter changes by -20% or $+20\%$, the price variance reduction ratio deviates more from 15.46% in the garlic market and 50.60% in the ginger market. Nevertheless, all price variance reduction ratios are positive, showing effects of price variance reduction under a 20% change of any parameter in both markets.

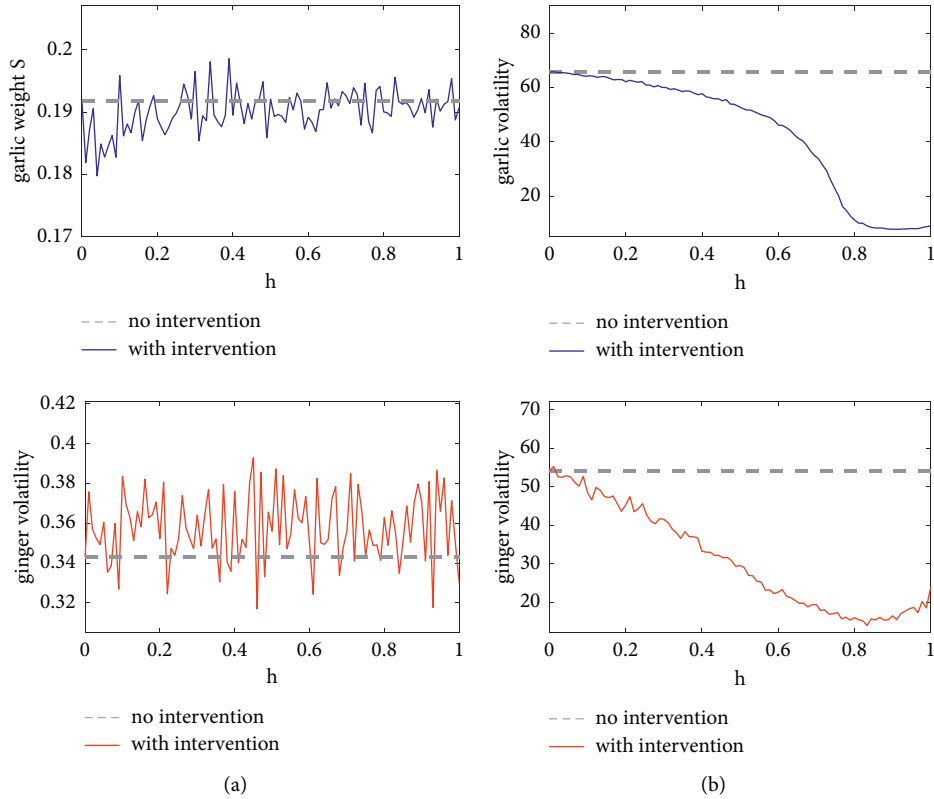


FIGURE 3: Intervention results of the government-guidance price policy. The figures show the average market fraction of speculators (weight S) and average price volatilities under different proportions of producers following government-guided price (parameter h). (a): The average market fraction of speculators is barely affected by the parameter h . (b): More producers following the government-guided price help to reduce price volatility.

TABLE 3: Price variance reductions due to intervention under alternative settings.

	Garlic				Ginger			
	Model parameter or $P_{e,t}^G$ varies by				Model parameter or $P_{e,t}^G$ varies by			
	-5 %	+5%	-20%	+20%	-5%	+5%	-20%	+20%
a	12.44%	11.92%	6.06%	19.98%	50.22%	50.79%	48.29%	38.42%
b	14.76%	9.60%	16.98%	12.48%	51.07%	45.71%	67.41%	48.94%
c	13.87%	10.58%	22.67%	4.22%	50.66%	50.36%	36.17%	46.12%
d	13.78%	15.26%	40.63%	24.72%	50.29%	50.51%	53.03%	50.71%
e	12.28%	13.94%	29.47%	39.12%	51.33%	52.65%	63.13%	77.22%
w	12.66%	16.94%	43.89%	1.87%	50.07%	55.11%	82.62%	25.18%
γ	15.02%	11.14%	13.91%	26.83%	50.51%	50.28%	46.06%	68.19%
ε	14.39%	18.11%	11.58%	33.56%	50.52%	50.93%	49.14%	55.26%
$P_{e,t}^G$	15.73%	13.92%	-3.31%	-39.12%	55.45%	50.57%	3.28%	-1.46%

The last row of Table 3 presents the results when the government-guided prices differ from the values used in Section 4. When the guided price changes by -5% or $+5\%$, the price variance reduction ratio is 15.73% or 13.92% in the garlic market and 55.45% or 50.57% in the ginger market, comparing with the initial 15.46% in the garlic market and 50.60% in the ginger market. The policy's effects are robust under a 5% miscalculation of the guided price. However, the central authority's obviously incorrect calculation of the guided price could lead to an ineffective intervention. If the guided price changes by -20% from the stable steady state, the

garlic price variance increases by 3.31% and the ginger price variance decreases by 3.28% . If the guided price changes by $+20\%$ from the stable steady state, the garlic price variance increases by 39.12% , and the ginger price variance increases by 1.46% . The government-guided price policy loses its efficacy under a 20% miscalculation of the guided price.

As a comparison between parameters and the guided price, it seems that the model result is more sensitive to the guided price. A comparison between garlic and ginger markets show that the model result is more robust in the ginger market.

6. Conclusions and Policy Implications

This paper develops and estimates an agent-based model filled with producers, consumers, and speculators to understand the role of speculation in market price dynamics and explore a low-cost price stabilizing policy. On the supply side, producers plan their production according to their price expectations. On the demand side, consumers and speculators coexist, and herding behavior driven by past speculative payoffs among buyers is allowed. A theoretical analysis of the model's nonlinear price dynamics shows that speculation can cause multiple steady states or even chaotic price behavior, destabilizing market prices. The model is estimated by the simulated method of moments and quarterly prices of garlic and ginger in China from 2006Q2 to 2018Q3. The model estimation results suggest that our model properly captures price dynamics in the garlic and ginger markets. Chinese garlic and ginger producers make production plans according to linear backward-looking expectations of product prices. The significant estimates of speculators' trend-extrapolating parameters verify the existence of speculative demand for garlic and ginger and provide evidence supporting speculation-driven price volatilities. In the policy experiment conducted upon the estimated model, we design a low-cost policy of releasing the theoretical steady-state price of the estimated model as a government-guided price to producers. This suggestive policy works through the supply side. When producers replace their old backward-looking expectations with the guided price, their output levels are adjusted accordingly, the product prices achieve market clearance change, and the simulated price variances of garlic and ginger drop. A larger fraction of producers following the policy positively correlates to lower simulated variances of garlic and ginger prices. Though such a supply-side policy barely reduces the average market fraction of speculators on the demand side, it decreases speculators' negative impact on market stability.

In the current model, speculators only participate on the demand side. In practice, speculators can also appear on the supply side. Future work should treat speculators as intermediaries involved in both the supply and demand sides. Besides, since the empirical data of product outputs are available, an agent-based model which integrates such data into simulation and estimation would be more convincing.

The government-guided price policy proposed in this paper is different from the reference prices usually seen in some farmers' markets in China. The former aims to guide farmers' production process, while the latter promotes fair trading between sellers and consumers. The reference prices in farmers' markets work by reducing the information asymmetry of market trading in local markets. They are provided by market managers and updated almost daily or at least weekly. Bargaining between individual sellers and consumers happens all the time. However, trading prices usually do not deviate much from

reference prices. This phenomenon is the rationale behind the assumption of our model that the consumers' expectation is consistent with the market price. With the help of reference prices and other information, consumption decisions tend to be made more quickly and easily compared to the time and effort the production process takes. The government-guided price policy proposed in this paper reduces the asymmetric information producers faced in the domestic market. The central government utilizes its information collection and calculation ability to help producers make more reasonable output plans and, therefore, better allocate their factors to the production of multiple agricultural commodities.

In the last few years, futures markets have quickly developed in China. An increasing number of agricultural products are taken as the underlying commodities of new futures. The introduction of corresponding futures satisfies the needs for hedging from the market demand side and helps to stabilize spot markets to some extent. Besides garlic and ginger, pork is a typical example of price booms and busts in China, although pork cycles are usually affected by swine fever. The latest pork bubble occurred in 2019 and 2020. Since the beginning of 2021, Dalian Commodity Exchange started trading live hogs. Pork prices dropped from 36 CNY/kg in January 2021 to less than 11 CNY/kg by October 2021. The introduction of live hog futures helped to burst the 2019–2020 pork bubble, demonstrating a positive example of futures stabilizing spot markets. Moreover, similar to apples and red dates, which already have corresponding futures traded in Zhengzhou Commodity Exchange, garlic and ginger are self-sufficient within the domestic market; there is no need to worry about risk transmission from international spot and futures markets. If possible, domestic commodity exchanges should seriously consider introducing new futures on garlic and ginger after a comprehensive investigation of market demand for such futures and a cost-benefit analysis. Before that, the low-cost government-guided price policy proposed in this paper is a worthy endeavor.

Data Availability

Empirical data are publicly available at <http://www.chinabric.com>. The simulated data and simulation codes can be obtained from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

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